

## Sensory-Feedback Exoskeletal Arm Controller

**Forces and torques are reflected from a robotic manipulator back to the human wearer.**

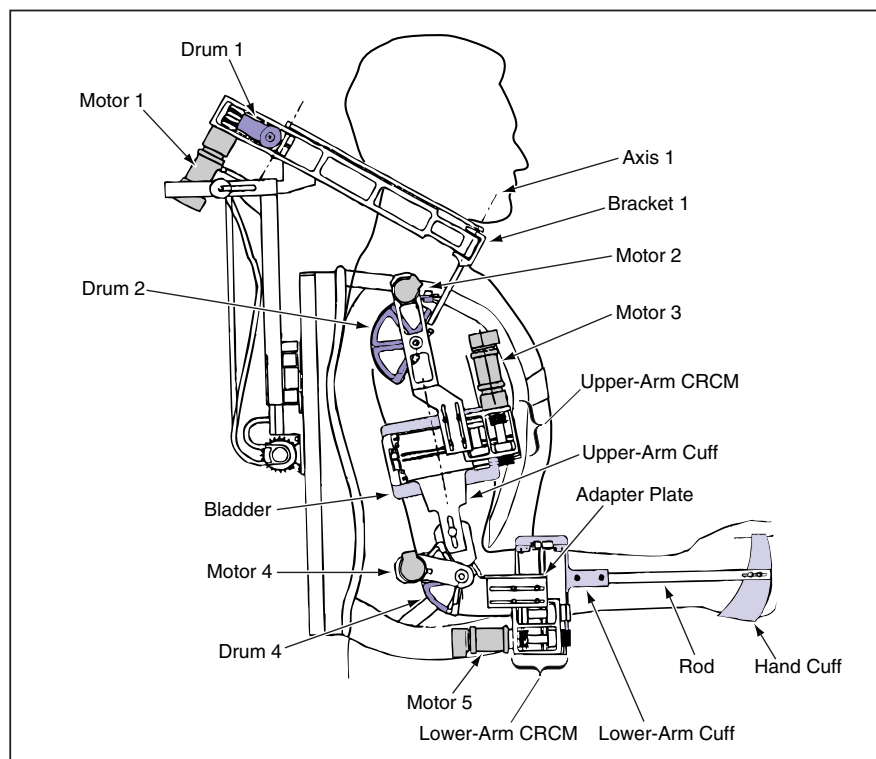
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An electromechanical exoskeletal arm apparatus has been designed for use in controlling a remote robotic manipulator arm. The apparatus, called a "force-feedback exoskeleton arm master" (F-EAM) is comfortable to wear and easy to don and doff. It provides control signals from the wearer's arm to a robot arm or a computer simulator (e.g., a virtual-reality system); it also provides force and torque feedback from sensors on the robot arm or from the computer simulator to the wearer's arm. The F-EAM enables the wearer to make the robot arm gently touch objects and finely manipulate them without exerting excessive forces.

The F-EAM features a lightweight design in which the motors and gear heads that generate force and torque feedback are made smaller than they ordinarily would be: this is achieved by driving the motors to power levels greater than would ordinarily be used in order to obtain higher torques, and by providing active liquid cooling of the motors to prevent overheating at the high drive levels.

The F-EAM (see figure) includes an assembly that resembles a backpack and is worn like a backpack, plus an exoskeletal arm mechanism. The F-EAM has five degrees of freedom (DOFs) that correspond to those of the human arm:

1. The first DOF is that of the side-to-side rotation of the upper arm about the shoulder (rotation about axis 1). The reflected torque for this DOF is provided by motor 1 via drum 1 and a planar four-bar linkage.
2. The second DOF is that of the up-and-down rotation of the arm about the shoulder. The reflected torque for this DOF is provided by motor 2 via drum 2.
3. The third DOF is that of twisting of the upper arm about its longitudinal axis. This DOF is implemented in a cable remote-center mechanism (CRCM). The reflected torque for this DOF is provided by motor 3, which drives the upper-arm cuff and the mechanism below it. A bladder inflatable by gas or liquid is placed be-



The **Force-Feedback Exoskeleton Arm Master** is designed for maximum comfort and low weight to minimize wearer fatigue. Its mechanism imitates the kinematics of the human arm.

tween the cuff and the wearer's upper arm to compensate for misalignment between the exoskeletal mechanism and the shoulder.

4. The fourth DOF is that of flexion and extension of the elbow. The reflected torque for this DOF is provided by motor 4 and drum 4, which are mounted on a bracket that can slide longitudinally by a pin-and-slot engagement with the upper-arm cuff to compensate for slight variations in the position of the kinematic center of the elbow. Attached to drum 4 is an adapter plate to which is attached a CRCM for the lower arm.
5. The lower-arm CRCM implements the fifth DOF, which is the twist of the forearm about its longitudinal axis. Motor 5 provides the reflected torque for this DOF by driving the lower-arm cuff. A rod transmits twist and torsion between the lower-arm cuff and the hand cuff.

With this system, the motion of the wearer's joints and the reflected torques applied to these joints can be measured and controlled in a relatively simple manner. This is because the anthropomorphic design of the mechanism imitates the kinematics of the human arm, eliminating the need for kinematic conversion of joint-torque and joint-angle data.

*This work was done by Bin An, Thomas H. Massie, and Vladimir Vayner of Exos, Inc., for Johnson Space Center.*

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